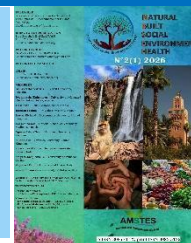




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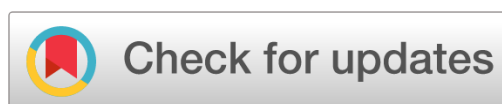


Development of Hydrophobic Coating and Spraying System for Corrosion Resistant Coatings

Andrius Patapas ^{1,a}, Aziz Fihri ^{2,b*}, Yassine Malajati ^{2,c}, Remi Mahfouz ^{2,d}, Waleed Al-Nasser ^{2,e}, Paul Luckham ^{1,f*}

¹Department of Chemical Engineering, Imperial College London , London, United Kingdom

²Advanced Materials Division, Research & Innovation Complex, Saudi Aramco , Dhahran 31311, Saudi Arabia



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^a **ORCID:** 0009-0008-3315-466X; **Email:** andrius.patapas15@imperial.ac.uk

^b **ORCID:** 0009-0000-0625-3568; **Email:** aziz.fihri@aramco.com

^c **ORCID:** 0000-0002-9053-7017; **Email:** Yassine.Malajati@aramco.com

^d **ORCID:** 0000-0003-0981-0440; **Email:** remi.mahfouz@aramco.com

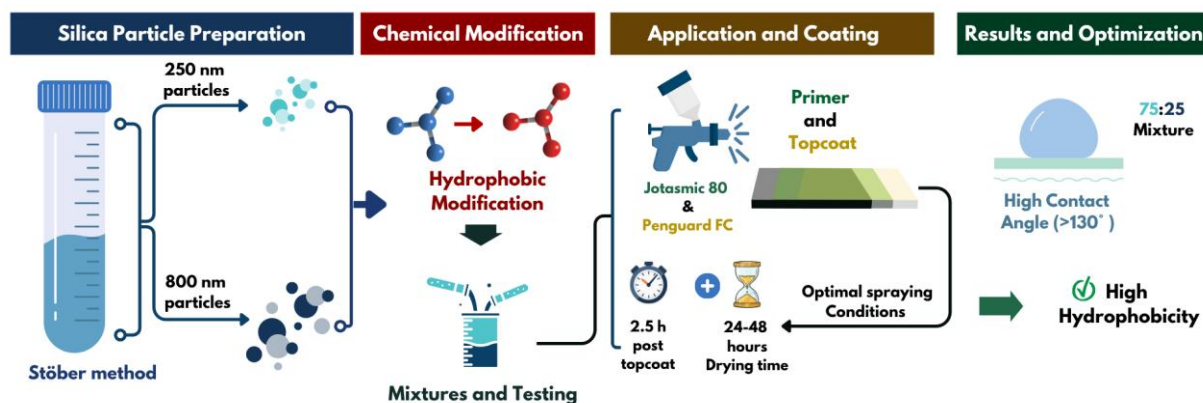
^e **ORCID:** 0000-0001-7372-9511; **Email:** Waleed.nasser@aramco.com

^f **ORCID:** 0000-0002-8191-540X; **Email:** p.luckham01@imperial.ac.uk

*** Corresponding authors:** Aziz Fihri , **Email:** aziz.fihri@aramco.com; Paul Luckham , **Email:** p.luckham01@imperial.ac.uk

Graphical Abstract

Hydrophilic silica particles of 250 nm and 800 nm were synthesized using the Stöber method and subsequently modified to obtain hydrophobic properties, confirmed by sessile drop measurements. Mild steel sheets were prepared, coated with Jotamastic 80 primer and Penguard FC topcoat, and then sprayed with different combinations of hydrophobic particles to form uniform coatings, which were evaluated qualitatively and through surface characterization techniques. The highest hydrophobicity (contact angle up to 140°) and optimal adhesion were achieved with a 75% (250 nm) and 25% (800 nm) mixture applied 2.5 hours after topcoat, with best structural formation observed after 24-48 hours of drying.



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Abstract: In this paper, hydrophilic silica particles (250 nm and 800 nm) were synthesized using the well-established Stöber method. The particles and their mixtures were chemically treated to achieve hydrophobic properties, confirmed using the sessile drop technique. Mild steel sheets were prepared, sand blasted and cleaned to the required surface roughness and cleanliness, verified by established quantitative methods. Two resins, Jotamastic 80 and Penguard FC, were applied as primer and topcoat to the required thickness. The resulting films were evaluated qualitatively and by optical interferometry and micrograph analysis. Samples were then coated with selected combinations of hydrophobic particles to form homogeneous coatings, and their hydrophobicity was assessed. The highest contact angle was obtained for a mixture of 75% 250 nm and 25% 800 nm particles, with other combinations showing contact angles between 130° and 140°. Optimal adhesion and hydrophobic performance were achieved when particle/ethanol suspensions were sprayed 2.5 h after topcoat application. The hydrophobic structure was best developed after 24–48 h of drying. Surface morphology was examined using Scanning Electron Microscopy, and the results are discussed.

Keywords: *Hydrophobicity, Steel structures, Spray coating, Contact angle.*

Introduction

Nature has long served as a source of inspiration for scientists, particularly in the study of natural surfaces that exhibit unique properties. One such example is the lotus leaf, which demonstrates superhydrophobic behaviour [1]. Inspired by such natural phenomena, researchers have focused on mimicking the micro/nanostructures of the lotus leaf to engineer synthetic superhydrophobic surfaces and develop innovative materials with enhanced properties [2]. These superhydrophobic surfaces have gained significant attention for their potential applications in various industries, including self-cleaning materials, anti-icing surfaces, drag reduction, oil-water separation and corrosion thanks to their excellent water repellency and antifouling properties [3,4]. But, their susceptibility to easy scraping and peeling remains a significant disadvantage that hinders their broader application in anti-corrosion fields. The fabrication of superhydrophobic surfaces requires combining suitable surface roughness with low surface energy materials and many processes have been explored to produce these surfaces, such as electrochemical deposition and plasma treatment, chemical etching and others [5-9].

Steel, a widely used material in industrial applications for its affordability and mechanical strength, is prone to corrosion in harsh environments [10]. The oil and gas company relied on cathodic protection, or coating to extend service life metallic structures and enhance safety and minimize economic losses [11,12].

Organic coatings, especially epoxy resins cured with amine agents, are frequently used to shield steel from corrosion. Despite these advantages, such coatings may degrade in marine environments under moisture exposure, leading to delamination and reduced durability. Nanoparticles such as silica, zinc oxide, titanium oxide, copper oxide, and fluorographene combined with polymers such as epoxy, polystyrene, polyurethane, and polydimethylsiloxane are being explored to develop superhydrophobic surfaces [13-18]. Silica is widely employed across industries because of its low cost, stability and versatile synthesis routes [19-22]. The Stöber method, the hydrolysis and condensation of alkoxysilanes in a basic medium, is commonly used to produce monodisperse silica particles with controlled properties [23]. To enhance their utility, the hydrophilic nature of silica can be transformed into hydrophobicity through processes like silanization [24,25]. In this study, hydrophilic silica particles of two sizes, 250 nm and 800 nm, were synthesized using the Stöber method. These particles were then modified to become hydrophobic and subsequently combined in different ratios. A combination of hydrophobic silica particles was dispersed in ethanol and applied via spraying onto an existing commercial epoxy coating system composed of both primer and topcoat layers. The highest contact angle was achieved using a mixture containing

75% 250 nm particles and 25% 800 nm particles. Other particle combinations also produced hydrophobic surfaces, with contact angles ranging between 130° and 140°. This study also outlines the optimized spraying conditions and parameters, such as dispersion concentration, flow rate, spray distance and topcoat drying time before application of the particle suspension.

Theory of Superhydrophobicity

The contact angle, θ is the angle formed when a liquid droplet in air meets a solid surface. It provides a measure of the relative strength of the interaction between the surface tensions at the three-phase contact line for two fluid phases and a solid surface (i.e., the border). It represents the ratio of the energy required to form a unit area of the solid-liquid interface to that required to form a liquid-air interface. This formalism was first proposed by Young in 1805 [26] and can be expressed mathematically as:

$$\cos \theta = \frac{\gamma_{SA} - \gamma_{SL}}{\gamma_{LA}} \quad (1)$$

where γ_{SA} , γ_{SL} and γ_{LA} are the surface tensions at the solid-air, solid-liquid, and liquid-air interfaces, respectively. Although this is known as the Young equation, the original paper by Young contained no equations. The limitation of this approach is that the relation applies only to perfectly smooth, homogeneous surfaces. This was modified over a century later by Wenzel [27], who introduced a roughness parameter, r , defined as the ratio of the true area of contact of the droplet to the apparent contact area, such that the effective contact angle θ_E (the actual measured contact angle) is related to the true contact angle, θ , by the relation:

$$\cos \theta_E = r \cos \theta \quad (2)$$

The Wenzel model assumes that the liquid penetrates the grooves associated with surface roughness. This condition may not always occur, particularly if the surface repels the liquid. This case was examined by Cassie and Baxter [28], who considered the surface to consist of a series of pillars, such that the droplet rests on the top of the pillars and does not penetrate the gaps between them. Under these conditions, the effective contact angle, θ_E , can be given by:

$$\cos \theta_E = \sigma \cos \theta_1 - \sigma_2 \quad (3)$$

where σ_1 and σ_2 represent the fractional surface area in contact with the droplet and the fractional surface area corresponding to the space between the pillars, respectively, and θ_1 is the true contact angle of the surface. It is widely agreed that the water repellency of biological surfaces is explained by the Cassie-Baxter model. For example, duck feathers exhibit a topographical network of 'barbs and barbules', and a water droplet deposited on them remains in a solid-liquid-air non-wetting composite state, in which tiny air pockets are trapped, giving rise to a high contact angle. The most well-known biological example of a high contact angle is the lotus leaf, where the contact angle of a water droplet is about 160° [29].

The leaves of many plants are coated with a thin waxy layer which, if smooth, is likely to exhibit a contact angle similar to that of smooth polyethylene, of about 100° [30], yet the lotus leaf is not smooth. Lotus (*Nelumbo nucifera*) is a semi-aquatic plant with circular leaves reaching up to 30 cm in diameter and displaying remarkable water repellency. The upper surface of the leaf features a distinctive hierarchical structure consisting of small protuberances known as papillae, which are themselves covered with a dense coating of agglomerated wax tubules, giving the leaf its superhydrophobic character [31]. A hierarchical surface structure that induces strong water repellency and contact angles above 150° is not unique to lotus leaves. Neinhuis and Barthlott [32,33] surveyed more than 200 plant species with contact angles greater than 150° , many of which are less exotic, such as nasturtiums and cabbages. The advantage to the plant is that such strong water repellency ensures that water rolls off the surface of the leaf rapidly, removing dirt and pests in the process.

Experimental

Materials

Tetraethyl Orthosilicate (TEOS), ammonia in the form of an aqueous solution with a concentration of 32 %, ethanol and heptane purchased from Sigma-Aldrich, UK and used without further purification. Trichlorododecylsilane was purchased from the Tokyo Chemical Industry Co., Japan without further purification. The specimens used for this work were hot-rolled mild steel sheets (BS EN 10025 - S275JR), with dimensions of 150 mm x 100 mm x 5 mm, sourced from Orion Alloys Ltd., UK. Jotamastic 80 coating used as primer and Penguard FC, used as a topcoat, were purchased from Jotun, UK.

Preparation of hydrophilic silica particles

Silica particles of two sizes, namely 250 nm and 800 nm, were synthesized in 10- litre batches according to the well-established Stöber method [20]. Depending on the required particle size,

different amounts of tetraethyl orthosilicate, TEOS, ammonia and ethanol were used (see Table 1 for synthesis details). In all cases the mixture was stirred using a magnetic stirrer for 24 h at room temperature. Afterwards, the mixture was left for three days in a fume cupboard which served two purposes. Firstly, some ethanol and virtually all the ammonia evaporated, meaning the remaining volume was roughly halved and was safer to handle; secondly, the larger particles settled under gravity, allowing the remaining ethanol to be decanted off. Subsequently, these particles were redispersed in approximately 1 litre of ethanol and then centrifuged at 4000 g for 10 minutes to remove any impurities. The particles were then redispersed again in a similar volume of ethanol. Redispersion was simple with no aggregates observable to the eye. The smaller silica particles did not settle without centrifugation, so these particles were then centrifuged at 4000 g for 10 minutes and redispersed in ethanol twice producing a final volume of approximately 1 litre. The particle size distribution for each batch of in-house synthesized silica particles was measured using dynamic light scattering (Malvern μ V instrument).

Table 1. Summary of synthesis conditions for the production of silica particles (~250 nm and ~800 nm) using the Stöber method.

TEOS (mL)	Ammonia (32 wt%) (mL)	Ethanol (mL)	Particle size (nm)
360	290	4500	~250
300	1500	3000	~800

Peak intensities for the batch of smaller particles were found to range between 220 nm and 290 nm (Figure 1), whereas those for the batch of larger particles ranged between 720 nm and 870 nm (Figure 2). Repeated measurements of independent samples allowed the mean particle size, polydispersity, and corresponding errors to be obtained (Table 2). Analysis using dynamic light scattering gave a polydispersity index of less than 0.05 for all samples, indicating that the samples were monodisperse, and that the errors were within reasonable limits

Table 2. Particle size measurements and corresponding statistics for silica particles with nominal sizes of ~250 nm and ~800 nm.

Particle size group	Mean particle size (nm)	Polydispersity index	Error (nm)
Small (~250 nm)	254.5 $\pm$ 4.6	0.020 $\pm$ 0.005	$\pm$ 26.6
Large (~800 nm)	803.6 $\pm$ 7.2	0.033 $\pm$ 0.008	$\pm$ 60.6

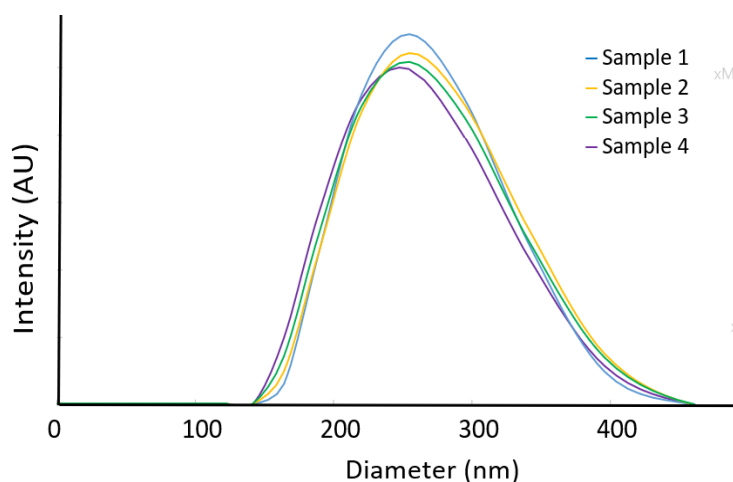


Figure 1. Particle size distribution of synthesized silica particles of smaller size

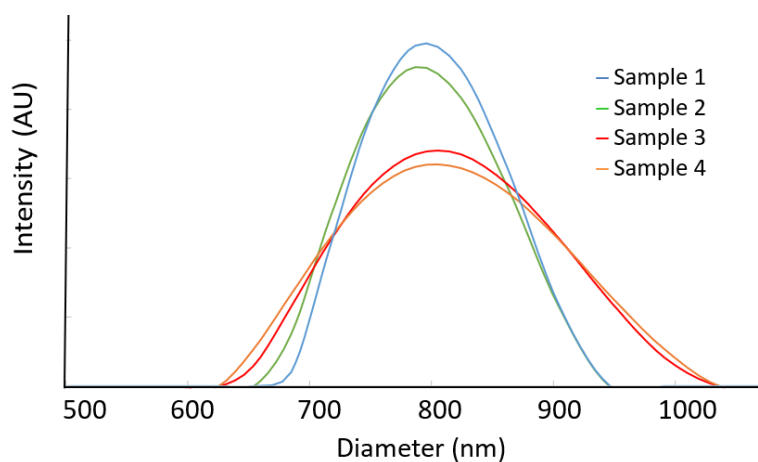


Figure 2. Particle size distribution of the silica particles of larger size

Preparation of Hydrophobic Silica Nanoparticles

Twenty grammes of silica particles, the small and large particles or mixtures thereof, were dispersed in 150 mL of dry heptane and stirred for 1 h at room temperature. The next step was to add 50 mL of trichlorododecylsilane; this mixture was stirred for 12 hours with a magnetic stirrer [29]. Particles were then centrifuged, washed in heptane, recentrifuged twice, and then dried in an oven set to 80 °C. The particles produced were noticeably hydrophobic. This procedure was conducted for the large silica particles, small silica particles and mixtures of the large and small silica particles. The mixtures investigated were by weight 25% large: 75% small, 50% large: 50% small. It was thought better to hydrophobe the mixtures of particles rather than mixing pre-hydrophobed particles owing to the difficulties of mixing powders, as opposed to suspensions.

Preparation of Hydrophobic Surface

The required by specification hot rolled mild steel sheets (BS EN 10025 - S275JR) cut to 150 mm by 100 mm (by 5 mm), were sourced from Orion Alloys Ltd., U.K. These coupons were abrasive blast using alumina powder followed by blowing with clean, dry, free of oil; compressed air was conducted in compliance with ISO 8501-1, which delivered cleanliness of near white metal (Sa 2 $\frac{1}{2}$). A residual dust level test was conducted in accordance with ISO 8502-3, and resulted in a rating of 1 [34]. Measurement of residual surface chloride was performed according to ISO 8502-6, and was found to be 35 mg/m² $\pm$ 15 mg/m². The surface profile of the blasted metal sheets was analysed using an optical interferometer, which confirmed the roughness to range between 40 μ m and 65 μ m (Figure 3).

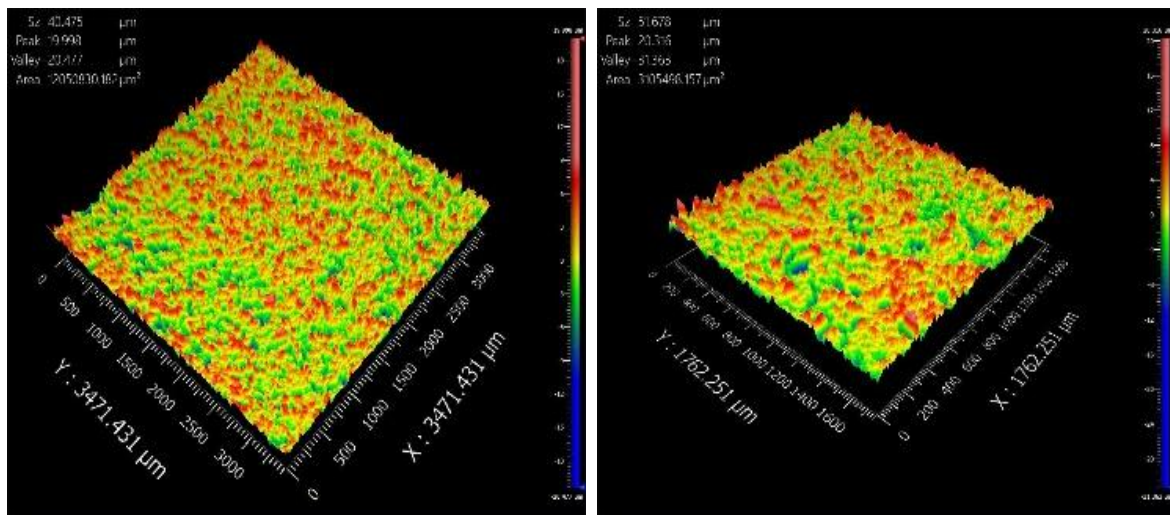


Figure 3. Typical surface roughness of the blasted metal sheet measured using optical interferometer (left: sample 1; right: sample 2)

After the aforementioned measurements and analyses of the blasted metal coupons, they were then firstly sprayed with the primer using a spray gun with compressed air at a pressure of 4 bar until the necessary film thickness was attained. The wet film thickness of the primer was measured using a hexagonal wet film comb and found to be about 210 μ m $\pm$ 30 μ m, which resulted in a dry film thickness of 150-200 μ m (the latter measured using Neoteck VTMTL610 meter). A drying period of 24 hours was allowed at room temperature (25 $^{\circ}$ C $\pm$ 1.5 $^{\circ}$ C). Following this, the topcoat was then sprayed under the same conditions as the primer until the wet film thickness was measured to be between 250 μ m and 300 μ m, which resulted in 160-210 μ m dry film thickness. Both coatings in the dry state need to be between 150 μ m and 200 μ m for optimal protection. Several metal

coupons were sacrificed to validate the spraying application method in terms of primer and topcoat film thickness. Three metal coupons were partially spray treated and the individual films allowed to dry. The film thicknesses of both the primer and the topcoat were confirmed to be within the required range using optical interferometer (Figure 4).

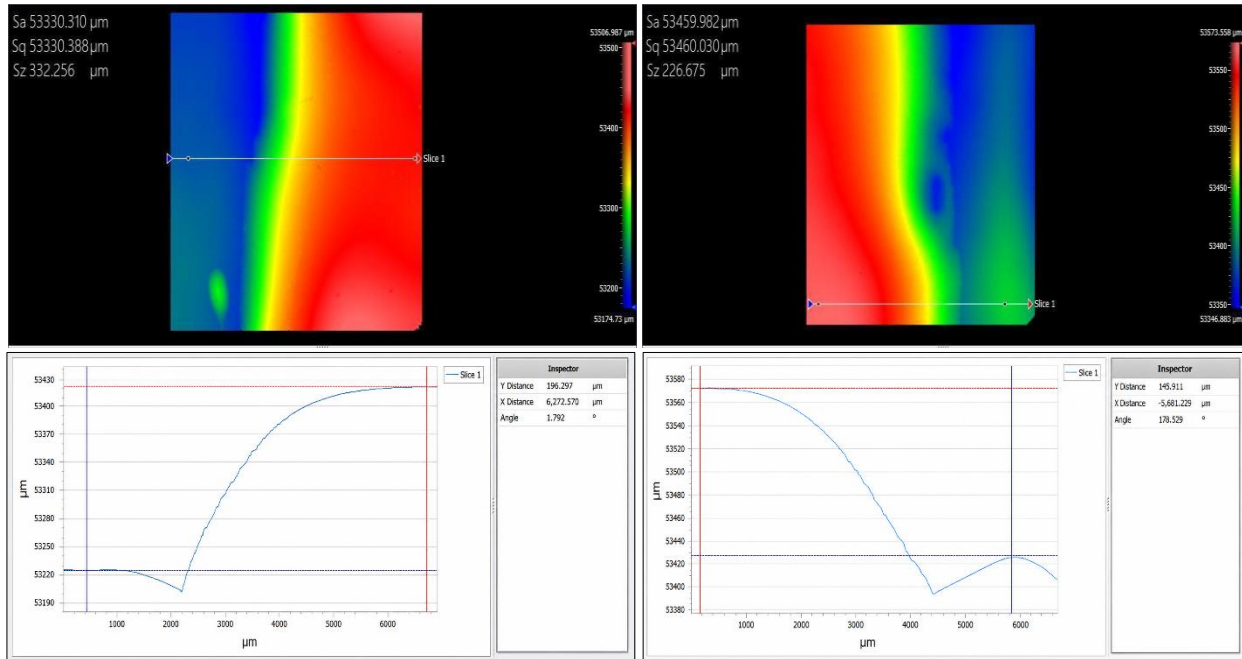


Figure 4. Dry film thickness of primer (left) and topcoat (right)

The temperature inside the fume cupboard where spraying was performed was recorded at 22.7 °C $\pm$ 1.5 °C, and relative humidity was 40 % $\pm$ 8%. At these conditions, the primer and topcoat (Penguard FC) were found to dry to a “touch-dry” state (i.e., the state of drying when slight pressure with a finger does not leave an imprint or reveal tackiness) after approximately 4 hours and 2.5 hours, respectively. The hydrophobic particle suspension in ethanol (2% w/w), produced by spraying application, was qualitatively evaluated for various conditions. Firstly, it was found that ethanol does not markedly result in swelling of the dry topcoat which would allow for particles to adhere to the surface. For this reason, spraying (distance 20 cm; flow rate 600 mL/min) was applied at different drying times from the initial application of the topcoat to determine whether particles would adhere to the surface of semi-dry film. Upon spraying and evaporation of ethanol from the sample surface, qualitative assessment in terms of adhesion, hydrophobicity, and homogeneity allowed to establish that at the aforementioned conditions the optimal drying time of the topcoat prior to spraying application of hydrophobic particle suspension is approximately 2.5 hours, which agrees with the supplied technical manual containing drying times for “surface touch dry” state, see Figure 5.

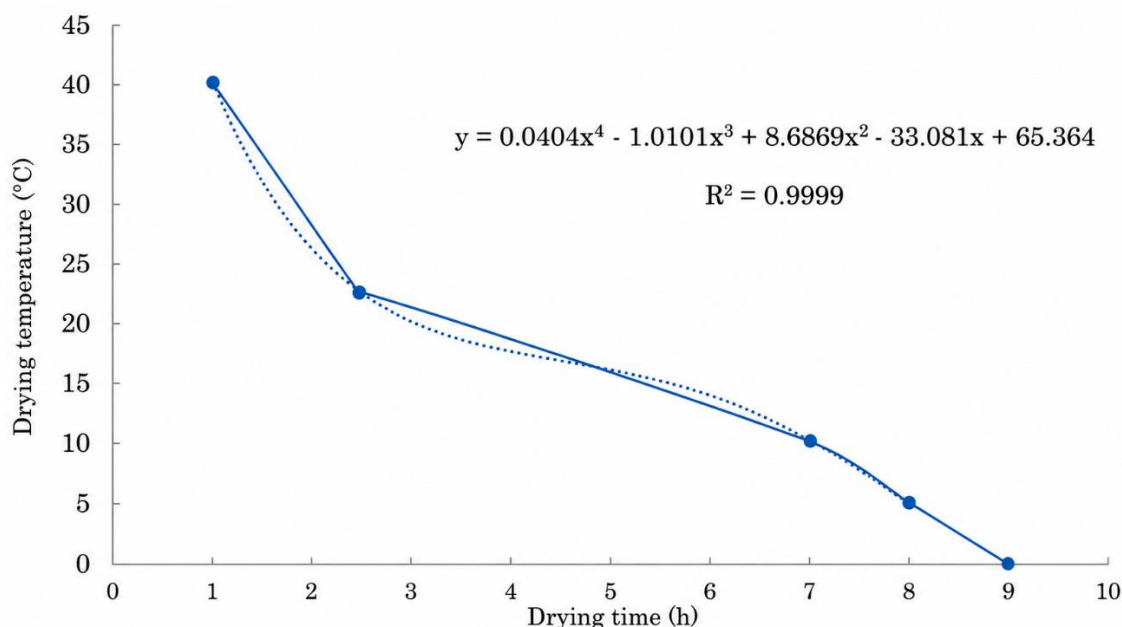


Figure 5. Drying time of topcoat to a surface touch dry state

Moreover, it was found that if the spraying is conducted before a critical drying time (i.e., below 2 hours period from topcoat application), the excess of ethanol was found to yield formation of cracks on the topcoat film upon drying, which were also not homogeneously filled with hydrophobic particles. This may lead to higher corrosion rates relative to treated metal sheets without such surface defects. On the other hand, if the drying is prolonged to 3.5 hours or longer, the extent of particle adhesion onto the topcoat significantly reduces. Considering potential differences in the spraying environment (e.g., temperature) for commercial applications, Fig. 5 shows the drying time for a different set of temperatures (data points extracted from Penguard FC technical manual). Using the plot, or 4th order polynomial fit ($R^2 = 0.99$), the corresponding drying time for “surface touch dry” state can be extrapolated for a required temperature.

Results and Discussion

Evaluation of Surface Hydrophobicity

Hydrophobicity of applied coatings was evaluated using sessile drop method (DSA25 Drop Shape Analyzer). Ultra-pure deionized water ($< 18 \text{ M}\Omega\cdot\text{cm}$) was used to form sessile droplets of 100-200 μL . The drops were imaged through a video camera and the contact angle (on both sides of the drop) was determined automatically through the software of the instrument. Measurements of contact angle of sprayed metal samples with different combinations of hydrophobic particle sizes were performed at various locations for random samples (see Table 3). Measurements were performed in 15 to 20 different locations for each metal sample and for five independent metal

samples; the standard deviation was calculated based on these measurements. The largest contact angle, i.e., 140° was found for a particle mixture containing 75% of 250 nm and 25% of 800 nm particles. Smallest size particles (250 nm) offer second to best hydrophobic performance (also $\sim 140^\circ$) likely caused by the formation of denser surface structures upon drying relative to the larger particles (800 nm). Those particles resulted in contact angle of 137° . A 50/50% combination led to lowest contact angle measured, i.e., 136° . The measured contact angle of the untreated topcoat with hydrophobic particles is below 90° (i.e., hydrophilic). No noticeable difference in the spraying process was observed among the four particle size combinations.

Table 3. Contact angle measurements of hydrophobic surfaces prepared using mixtures of small (~ 250 nm) and large (~ 800 nm) silica particles

Hydrophobic particle composition (% w/w)	Sample 1 ($^\circ$)	Sample 2 ($^\circ$)	Sample 3 ($^\circ$)	Average ($^\circ$)	Standard deviation ($^\circ$)
100% 250 nm	137.7	140.4	141.4	139.8	1.6
100% 800 nm	135.1	136.9	137.9	136.6	1.2
50% 250 nm / 50% 800 nm	133.7	136.5	137.1	135.8	1.5
75% 250 nm / 25% 800 nm	139.1	140.5	141.2	140.3	0.9
Topcoat (0% particles)	78.3	88.0	83.2	83.2	4.0

Evaluation of Surface Morphology

Firstly, samples with topcoat only (absence of hydrophobic particles) were analysed. In the Figure 6a a magnified image of the surface reveals defects in coatings in the form of pores with diameters <1 mm. Optical micrographs, shown in Figure 6b, reveal the pore size range between $33\text{ }\mu\text{m}$ and $220\text{ }\mu\text{m}$. The most likely cause for such defects is the air entrainment during the high-speed spraying procedure. The high aspect ratio surfaces (i.e., edges) were found to be covered with non-uniform coating (Fig. 6c). Dripping of the excess coating is also observed at the edges particularly at the corners of the square samples. Such variation in thickness may result in ineffective coating properties for a metal surface, being either below or above the recommended thickness notified by the supplier.

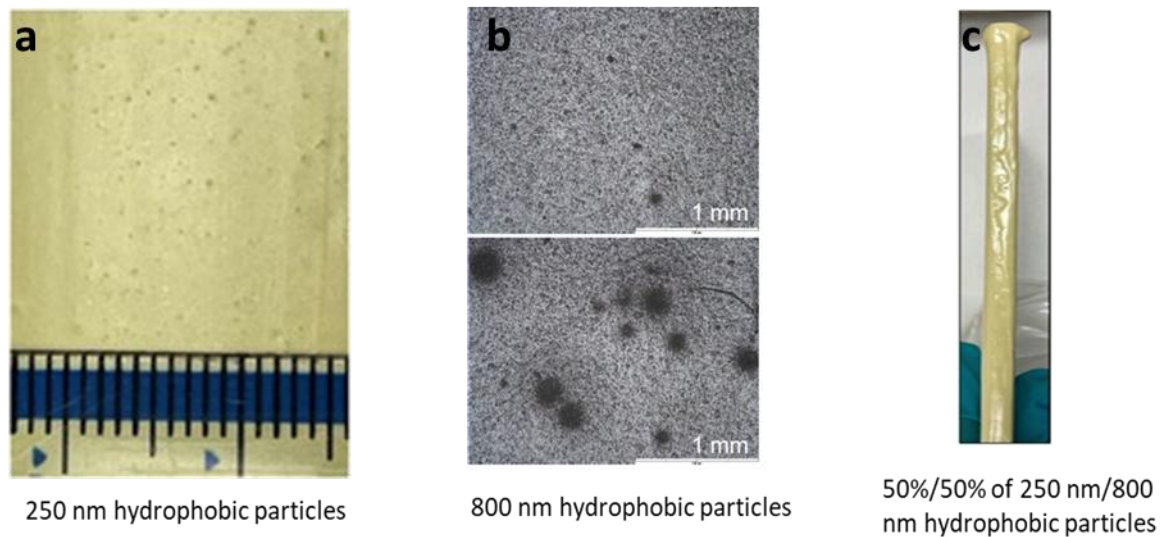


Figure 6. Contact angle measurements of metal sheets sprayed with selected combinations of hydrophobic particle mixtures.

Samples with topcoat only were further analysed using SEM. From Figure 7 it is observed that the dried topcoat layer forms a nearly continuous surface with occasional surface defects. These defects appear as non-uniform holes (possibly micro-pores) through the bulk varying in size (typically $<10\ \mu\text{m}$), which reveals complex structure of the bulk interior and potential pathways against intended metal surface protection.

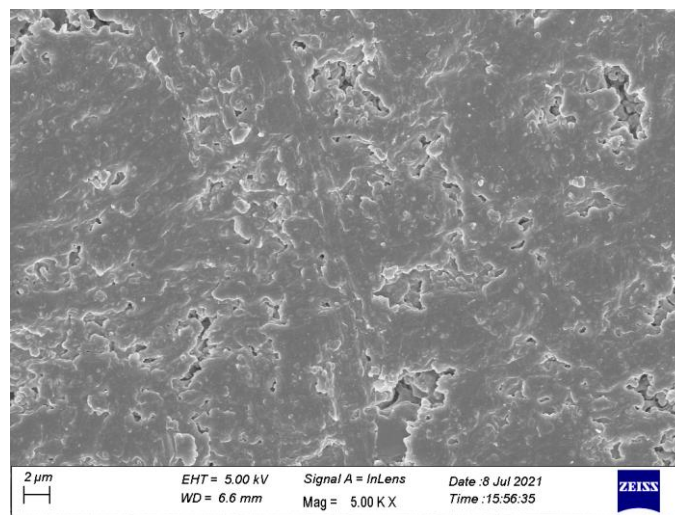


Figure 7. SEM showing surface morphology of topcoat without hydrophobic particles

Qualitative study for adhesion and surface hydrophobicity showed that the treated surfaces with hydrophobic particle suspension require at least 24 hours of drying time, and for best results 48 hours. Below these drying times it was found that the deposited water droplets on the treated surfaces have contact angles of less than 90° with rapid spreading of water drop. The final dried

samples overall appear to have a homogeneous layer of hydrophobic particles (Figure 8). Some areas were found to be only partly covered with hydrophobic particles particularly at the edges. Spraying the edges of the metal sheets was found to be not very effective in terms of particle deposition because of the strong spraying stream of the particle/ethanol suspension, which did not sustain on the surface but flowed off vertically down over the main surface. In addition, some areas, particularly close to the edges, are seen to have higher particle concentration than the others. This was probably caused by the uneven volume of particle/ethanol suspension sprayed, which at places accumulated into droplets instead of a thin film, and upon evaporation ethanol droplets contracted resulting in locally higher particle concentration. Generally, it was found that spraying of 2% w/w particles in ethanol suspension required a repeated application of up to 10 times, where post each spraying application ethanol is required to evaporate for the particle to adhere to the surface of the topcoat. An alternative particle concentration of approximately 20% w/w in ethanol was tested, which showed that only up to two spraying applications were required to cover the topcoat surface evenly with chosen hydrophobic particles. Since the spraying system can handle such concentration for a prolonged time prior to cleaning, it may substantially reduce overall spraying process time and improve productivity. Upon measurement of contact angles at different locations of all samples with hydrophobic particle coating it was found that the hydrophobicity was varying between $\sim 9^\circ$ and $\sim 130^\circ$, in agreement with qualitative observations on homogeneity of the coating. Areas of varying hydrophobicity were marked and further analysed using SEM. In locations with low contact angles (90°), hydrophobic particles are found to form agglomerates and clusters potentially being partially covered in the topcoat material (Figure 9). Some particles were observed to be embedded in the bulk topcoat. Only a small fraction of the treated area is covered by hydrophobic particles that would increase hydrophobicity.

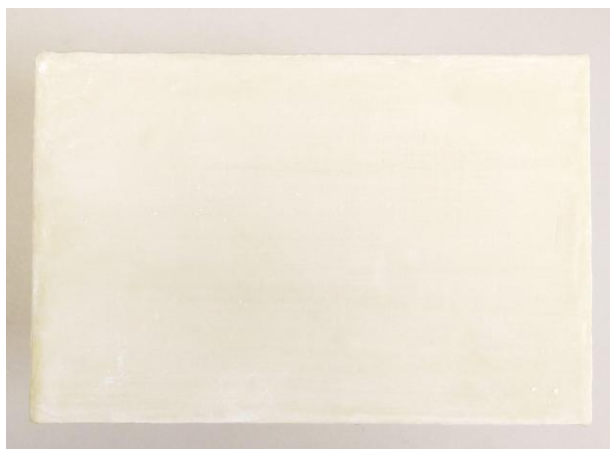


Figure 8. Photograph of fully treated metal sheet with 100% of 800 nm hydrophobic particles (~ 48 h of drying of hydrophobic coating)

In these circumstances, it is important to note that the contact angle is still above the value of samples with topcoat only, yet, is delivering very limited required enhanced material properties. Those areas that have contact angles of 130° and above are measured to have homogeneous coverage by hydrophobic particles as evidenced using SEM images (Fig. 10). From this, one can also see that an insignificant proportion of particles is also embedded in the topcoat layer and some formation of agglomerates, yet delivering required material properties in terms of hydrophobicity. Such differences may have occurred because of a marginally uneven topcoat film thickness throughout the surface, producing variable areas of dryness. In turn, spraying of ethanol/particle suspension under the given conditions resulted in higher interaction with the topcoat film. Spraying edges of the metal sheets was found to be not very effective in terms of particle deposition because of the strong spraying stream of the particle/ethanol suspension.

This did not sustain on the surface but flowed off vertically down over the main surface. In addition, some areas, particularly close to the edges, are seen to have higher particle concentration than the others. This was probably caused by the uneven volume of particle/ethanol suspension sprayed, which at places accumulated into droplets instead of a thin film. Upon evaporation ethanol droplets contracted, resulting in locally higher concentration. So, on edges it was difficult to meet homogeneous film thickness. The spraying of hydrophobic particles was also found rather ineffective in these areas. Figure 11 below shows that the area close to the edge and the sides has poor hydrophobic particle distribution. Such configuration along with non-homogeneous primer and topcoat film thickness leaves the edges and side surfaces most vulnerable to potential damages that may be prone to more rapid corrosion.

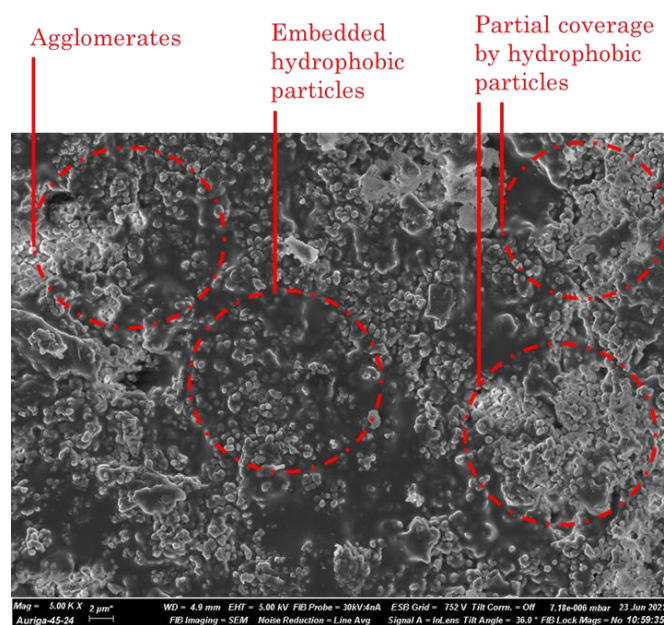


Figure 9. Surface morphology using SEM for surfaces with sessile drop contact angle $\sim 90^\circ$

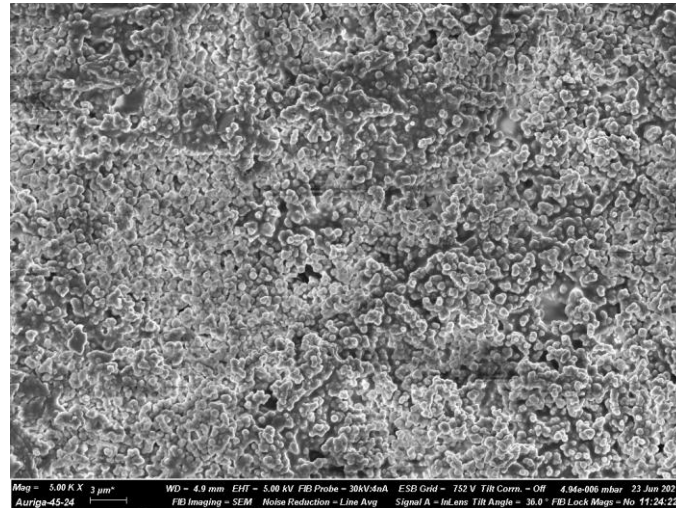


Figure 10. Surface morphology using SEM for surfaces with sessile drop contact angle $\sim 125^\circ$

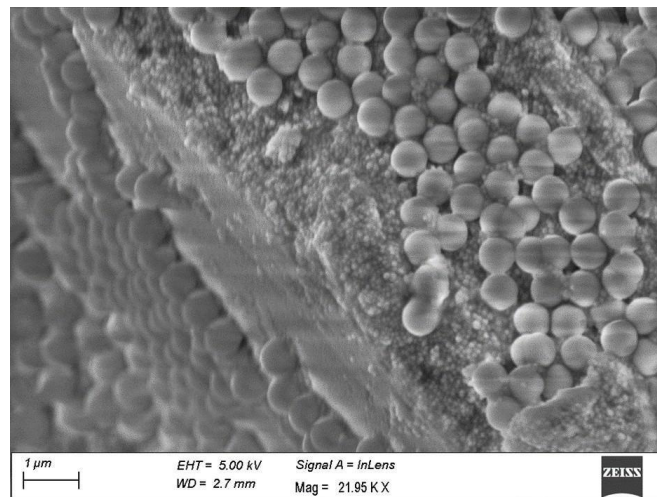


Figure 11. Surface morphology using SEM for surfaces at the edge of coating with hydrophobic particles

Conclusions and future work

Mild steel samples have been prepared according to relevant BS and ISO standards. The required surface roughness was validated using an optical interferometer. Using a spraying system two coatings of required thickness were applied consisting of primer and topcoat. Surface morphology of thick dried topcoat layer is observed to form a nearly continuous surface with occasional surface defects i.e., micropores that range in size between several to hundreds of micrometres. Four different combinations of synthesized hydrophobic particles,

consisting of 250 nm and/or 800 nm, were applied to a semi-dry topcoat film to allow for particle adhesion with an aim to create a hydrophobic surface layer. SEM analysis has shown that in areas

with low contact angle (90), hydrophobic particles are found to form large agglomerates and clusters, which are probably embedded/covered in the topcoat fluid itself.

In areas with high contact angle ($>130^\circ$) hydrophobic particles are found to be partially embedded and covered across the whole topcoat surface with little to no agglomeration. A vast area at the edges of treated samples was found to contain very few hydrophobic particles, suggesting that particle application by spraying was inefficient. Best performing hydrophobic particles in terms of contact angles were found for 100% of 250 nm size and a combination of 75%: 25% of 250 nm and 800 nm, both delivering hydrophobic coating with $\sim 40^\circ$ contact angles.

This study demonstrates a straightforward method for developing hydrophobic coatings and future research is advisable to evaluate the performance of these coatings and their chemical stability including the bonding between silica particles and the polymeric matrix and assessing corrosion durability under real-world conditions. The catastrophic failures in critical assets like oil and gas platforms can lead to devastating outcomes, including multiple fatalities, massive property damage, and total facility loss. These incidents often result in large-scale environmental harm, such as significant oil spills or toxic releases that require full evacuations, alongside severe operational delays and long-term economic disruptions to national infrastructure and government functions.

These epoxy hydrophobic coatings are expected to deliver significant socio-economic benefits, including reduced maintenance costs, enhanced energy efficiency, and extended asset lifespan. Ultimately, this research aims to evaluate the efficiency of these potential protective treatments to validate their suitability for practical applications, thereby integrating sustainability criteria to drive innovation within the oil and gas industry. In addition, the findings of this study open the door to explore the benefits of these hydrophobic coatings for a new generation of nanocomposites with advanced functional properties.

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